ARMY RESEARCH LABORATORY

Sand Erosion Test Method for DOD Unique Environments

by Lynne Pfledderer and Marc Pepi

ARL-RP-229 **September 2008**

A reprint from the *Proceedings of the 2007 Tri-Service Corrosion Conference*, paper 1783, Denver, CO, 3–6 December 2007.

NOTICES

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Sand Erosion Test Method for DOD Unique Environments

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14. ABSTRACT

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15. SUBJECT TERMS

solid particle erosion, mass loss, volume loss, Army helicopter rotor blades, sand erosion, size distribution, mineralogy, angularity, roundness

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SAND EROSION TEST METHOD FOR DOD UNIQUE ENVIRONMENTS

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ABSTRACT

The geologic and physiographic setting of Southwest Asia (SWA) makes this region one of the worst environments for erosion damage of rotor blade and leading edge aerospace components. In 2005, observations of actual SWA field failures of helicopter rotor blade protective tapes and coatings were compared to existing state-of-the-art, laboratory-based sand erosion data during a US Army sponsored program. Laboratory produced data did not match the severity of field-use damage, even under extremely high levels of particle loading. The need to test to erosive failure representative of this environment was determined to be paramount in establishing relative performance levels of erosion resistant protective systems being screened for potential field use. The goal of this effort is to provide two synthetic sand formulas capable of testing various polymer-based candidate rotor blade protective systems to failure. The test media will be derived from characterization of sand and dust materials unique to SWA. The synthetic sand mixtures developed by this effort will be incorporated in a new test protocol for sand erosion to represent a truly “worst case” test, with extended application to other aerospace components susceptible to sand erosion damage applicable to Department of Defense (DoD) activities in most dry – hot desert regions.

Keywords: sand erosion, rotor blades, size distribution, mineralogy, angularity, roundness

INTRODUCTION

The durability properties of rotor blade protective systems are in need of improvement across all agencies in the DoD. Deployments in SWA have highlighted the prevalence of premature failure of current rotor blade protective systems and result in costly and time consuming repair operations. The screening and down selection of rotor blade protective systems depends upon several durability-related laboratory tests, one of the most significant being sand erosion. Unfortunately, the few standards that exist defining requirements for sand erosion testing, such as MIL-STD-810 and MIL-HDBK-310, fail to specify sand media much past particle size and concentration (Reference 1, 2, & 3). No validated test standard exists for sand erosion whereby developers and manufacturers of blade materials and systems can assure the DoD of improved real-world performance. Without such a standard, any industry claim about improved sand erosion resistance is relative, forcing the down selection of materials to be whatever test "standard" a particular vendor believes is most appropriate.

It was not until 2003 that Southwest Research Institute recognized and attempted to better define particulate distribution and mineral composition (Reference 4). This effort was groundbreaking with the positive identity of minerals, other than quartz, that are characteristically angular in shape which could significantly impact the severity of erosion damage on rotor blade protective systems. In addition, the presence of clay was identified. These findings were substantiated in a few other programs to follow (References 5, 6, & 7). In one of these programs, the Army Research Laboratory (ARL) performed erosion testing on baseline materials found on Army aviation rotor blades (Reference 8). In addition to characterizing the foundry sand utilized for testing via scanning electron microscopy, this characterization was contrasted with sand retrieved from two different areas in Iraq. The Iraqi sand grains were shown to be covered with a clay-like dust, a feature not addressed in media used for sand erosion testing.

A review of exploratory soil maps available for those SWA countries of interest, in addition to climatic data available through the Air Force Combat Climatology Center, substantiated the need to better characterize particulate size, angularity, and mineral composition of sand due to the presence of mountainous regions, river beds, and deltas typical of the operational environment. It is recognized that the season of occurrence, wind direction, and amount of particulate matter for dust storms varies by locality. Also, the origin and nature of dust storms depend on general weather conditions, local surface conditions, and seasonal conditions. In spite of these variations, the fact that weapon systems are continuously exposed to some form of blowing dust, sand, or silt should not be ignored by aerospace material developers and manufacturers.

EXPERIMENTAL PROCEDURE

The influence of sand particulate characteristics on the rate of erosion damage on rotor blade protective systems is the main focus of this program. Sand and soil specimens from SWA are the main interest for this effort, but samples were also obtained from a variety of sources and locations. In addition, sand and soil samples from various North American locations were obtained for comparative purposes.

Sand samples from several SWA and other regions were characterized to determine particle sphericity and degree of angularity; the composition of the particles; the amount and type of clay present; and grain size and mineralogy. Characterization of these samples was accomplished by optical microscopy and petrographic analysis techniques. These natural specimens were prepared for

characterization using standard particulate preparation methods used in geological mineralogy analysis. There are three sample preparations typically used to examine particulate media. These are polished sections for grain size and shape analysis, petrographic thin sections for mineralogical and textural analysis, and grain mounts for general particulate description and sample overview. The grain mounts are also used to cross check and confirm determinations from the other two sample preparations. Grain mount findings will not be discussed in this paper.

The specimens were mixed with an optical epoxy fixative and cast into small round slugs. These slugs were approximately 0.25 inches in diameter by 0.5 inches long. It is possible for the material to settle and become size sorted during casting. For this reason, each formed billet was placed on its side in a 1 inch diameter mold to accommodate this behavior by using a second optical epoxy casting step. The resulting pucks (Figure 1) were then sectioned to expose a cross sectional area from the base to the top of the billet. The thin slice of sample cut from the puck was used to prepare a petrographic, thin section (Figure 1) for each of the specimens. The pucks were then polished to provide polished mounts for each of the specimens.

FIGURE 1 - Polished Puck and Petrographic Thin Section Specimens

Shape analysis was performed via reflected light examination of the puck specimens. The images were analyzed with the freeware "Image Java" program available from the National Institutes of Health. The grayscale reflected light image is processed by using a 'threshold' function to turn all of the grains of interest into black shapes and the remainder of the field of view to white. Image Java has a number of functionalities that are useful in particle shape analysis. One of these subroutines is "particle analysis." This subroutine counts pixels in the black spots for grain area, as well as around the perimeters of the spots for circumference. It is possible to extract actual dimensions if the program has been calibrated to the pixels per meter scale for the samples of interest. The resulting values generated are the true area of individual grains and their true circumference. The images can also be measured for features such as the smallest circle that can encompass the grain, the aspect ratio of the two major axes of a grain, and so on.

The analysis of the sand data can take several forms from simple side by side comparison to statistical size distributions. The measurements of greatest concern for this study were the ratio of the apparent circumferential radius (R_C) to the apparent area radius (R_A), as well as the aspect ratio of the grain. A large circumferential to area radius ratio value (R_C/R_A) declares that the average roughness or angularity of a grain is very large meaning that the grain is pointy. However, this number is mediated by the degree of elongation of a particular grain. The most elongated, pointy grains are those with the largest R_C/R_A ratio *and* the greatest aspect ratio. This resulting plot is a direct analytical measurement of the Krumbein Scale (Figure 2) without having to visually guess what the actual Krumbein value is for a

particle. The Krumbein scale is shown in Figures 3 and 4 after having been evaluated using Image Java. Note that in Figure 4, the R_C/R_A ratio was expanded for illustration purposes.

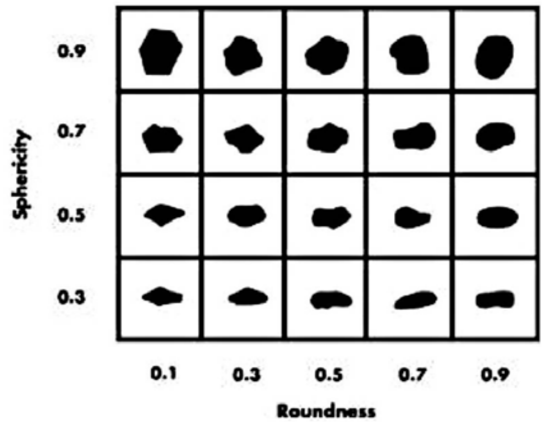

FIGURE 2 - Krumbein Scale for Particle Roundness/Sphericity

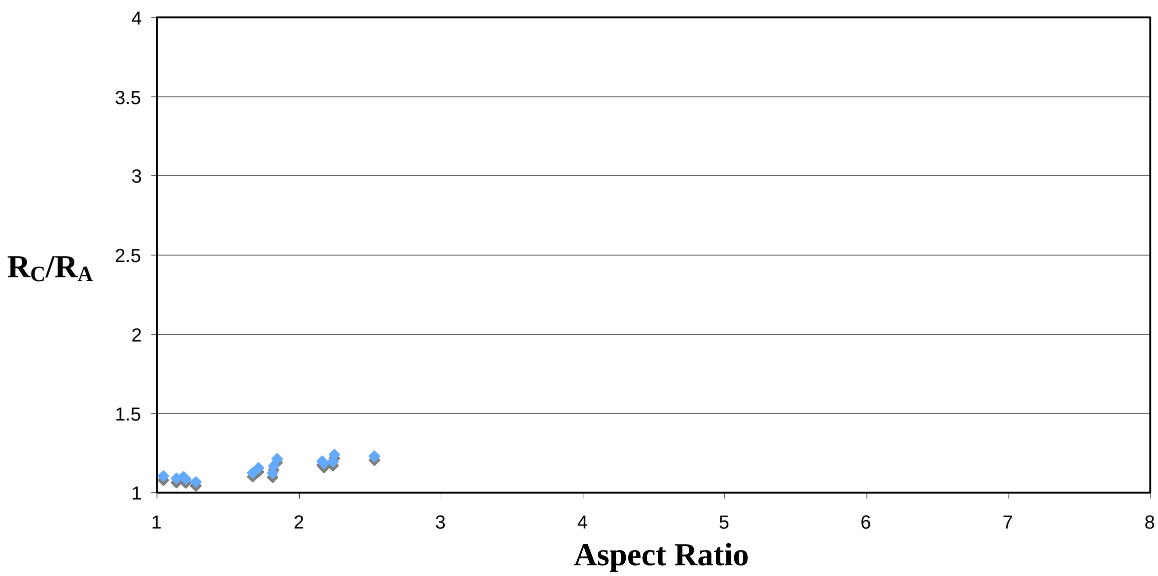

FIGURE 3 - Krumbein Scale Quantified Using Image Java

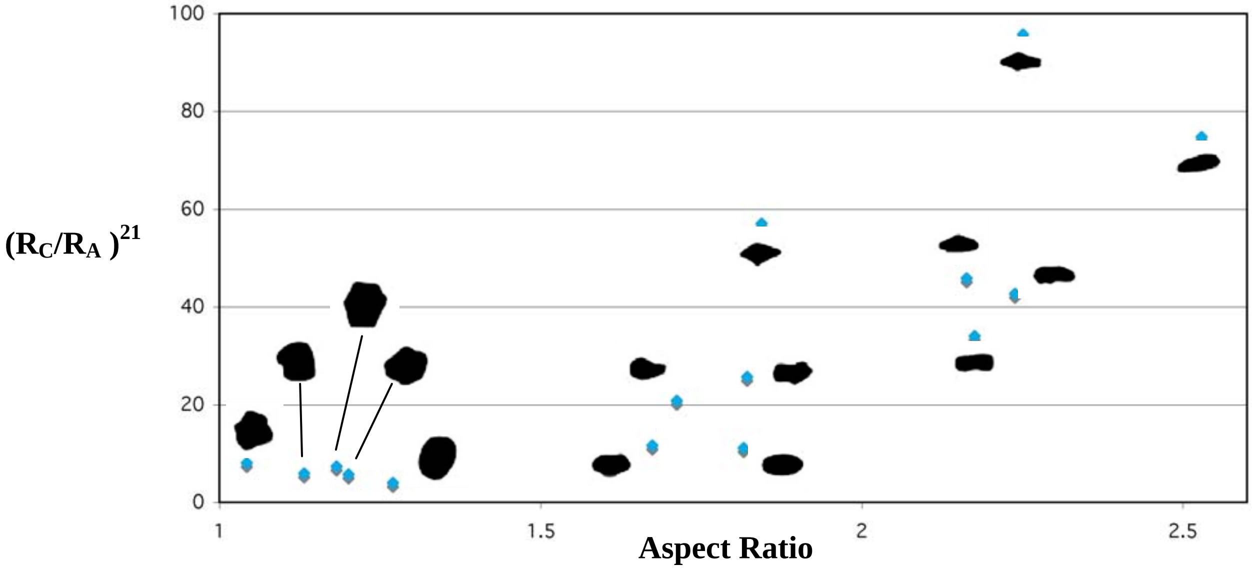

FIGURE 4 - Zoomed in Krumbein Scale Quantified Using Image Java

Mineralogical analysis was performed via petrographic analysis of thin sections of the pucks. This analysis used the optical behavior of the sand grains when they were positioned between Polaroid films that had been crossed at 90 degrees to prevent light from passing between them. The presence of various minerals in the samples will exhibit distinctive optical properties when viewed in this manner.

Following a limited sand characterization and analysis, some preliminary sand erosion testing was accomplished utilizing the Air Force Research Laboratory (AFRL) Particle Erosion Apparatus under ambient conditions to assess the erosion resistant performance of polyurethane tape specimens exposed to a commercially available golf sand media (as used in professional golf course bunkers), with and without the addition of dust from Yuma Proving Ground (YPG) at a 30 degree angle of incidence for simulated speeds of 500 and 672 miles per hour (mph).

RESULTS

The Image Java plots of R_C/R_A versus Aspect Ratio and reflected light images for seven sand samples are provided in Figures 5 through 18. The commercially available foundry and golf sand samples (Figures 6 and 8) are of a 100 percent quartz mineral composition. However, a variety of other minerals were present in the natural sand specimens, each of which varied depending on the source location of the sand. The presence of clays and silt was evident in nearly all of the natural sand specimens. The actual clay composition for sand samples is still being determined.

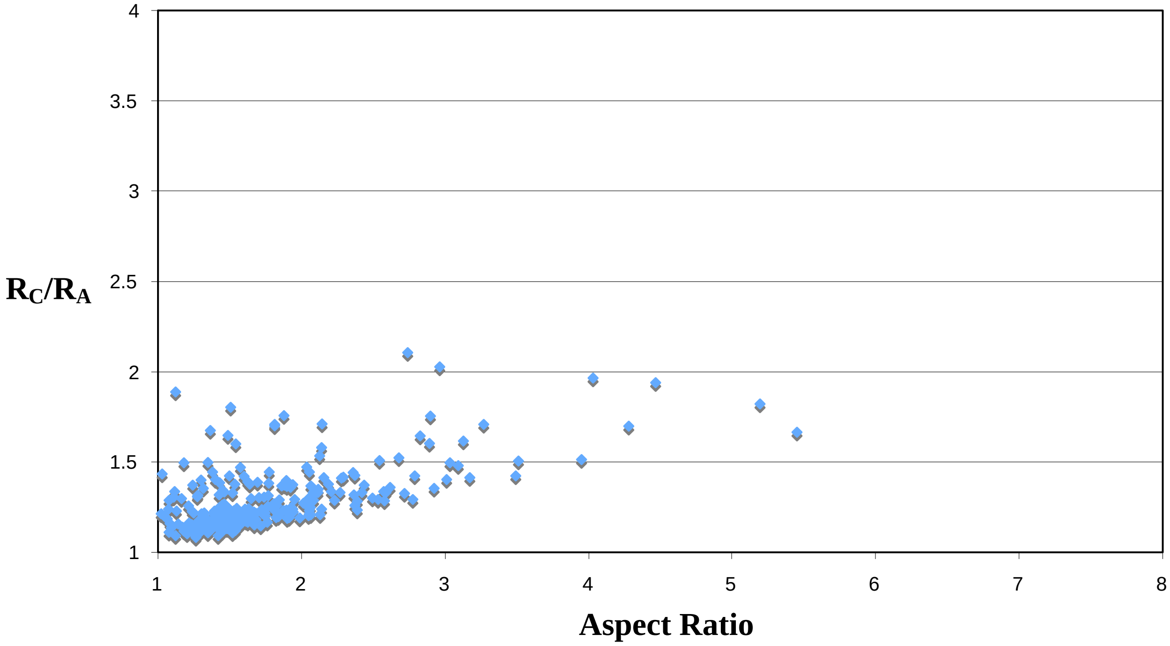

FIGURE 5 - Distribution of 144 to 177 µm Commercially Available Foundry Sand Sample

All of the grains in Figure 6 are quartz. The black circular features seen in this image, in addition to all of the reflected light images, are air pockets typical of the sample preparation process and not a feature of the sand samples. The grains in Figure 6 are very well sorted.

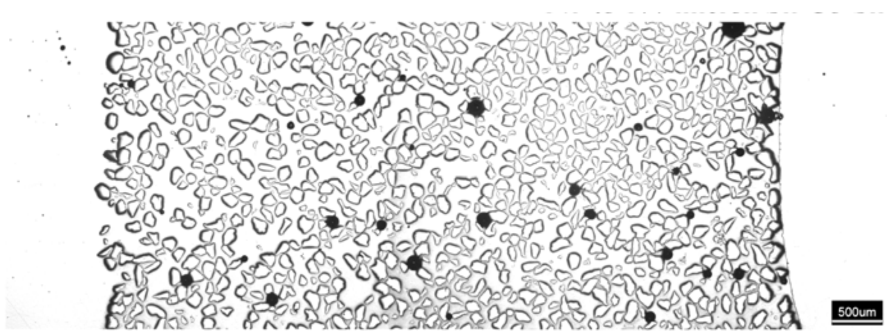

FIGURE 6 - Reflected Light Image of 144 to 177 µm Commercially Available Foundry Sand Sample

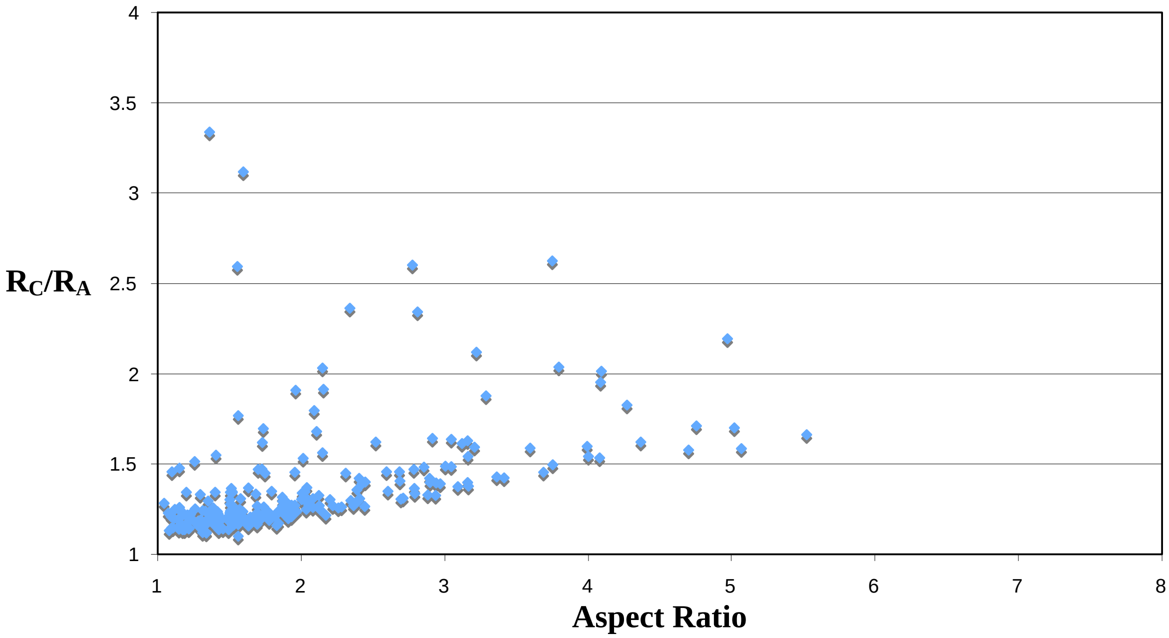

FIGURE 7 - Distribution of 500 to 850 μm Commercially Available Golf Sand Sample

All of the grains in Figure 8 are quartz. A comparison of the plots in Figures 5 and 7 show different distributions, particularly for R_C/R_A values greater than 2.5. The reflected light images in Figure 8 are markedly more angular than those in Figure 6. The grains in Figure 8 are moderately sorted.

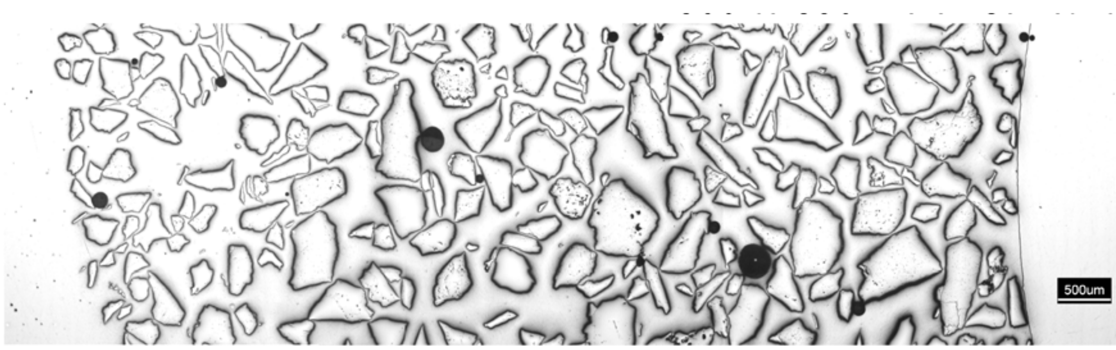

FIGURE 8 - Reflected Light Image of 500 - 850 μm Commercially Available Golf Sand Sample

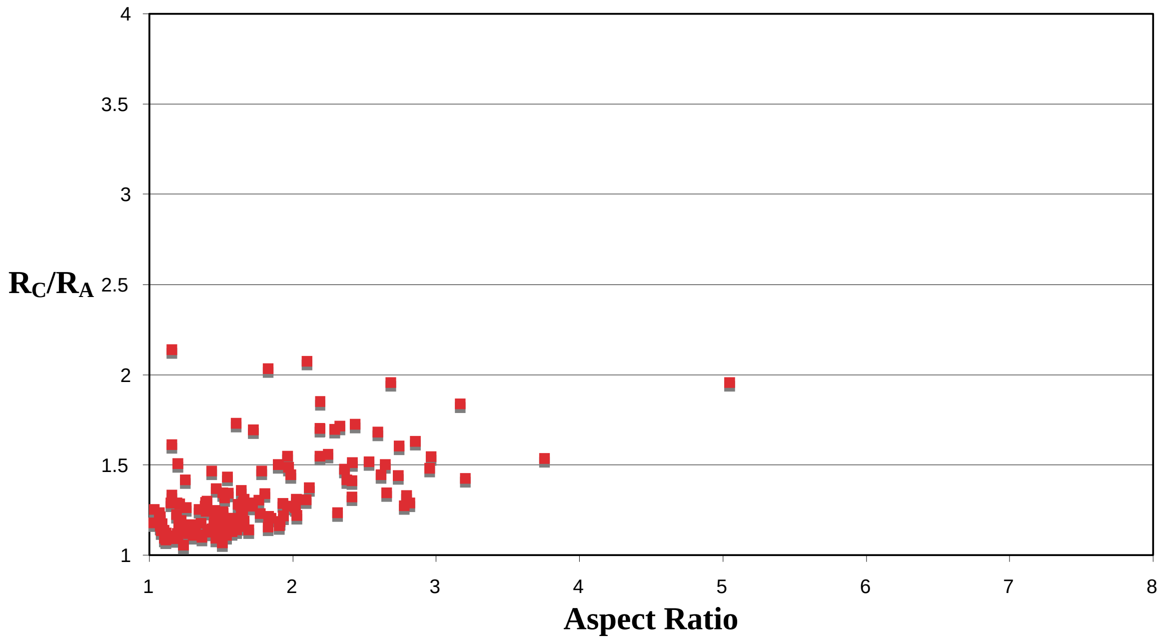

FIGURE 9 - Distribution of YPG Sand Sample

The distribution plot for Figure 9 is similar to Figure 5. However, the mineral grains in Figure 10 are quartz, feldspars, pyroxenes and amphiboles, black oxide minerals, and a large quantity of silt and clay particles. The large circular black feature is an air pocket. The grains in Figure 10 are poorly sorted.

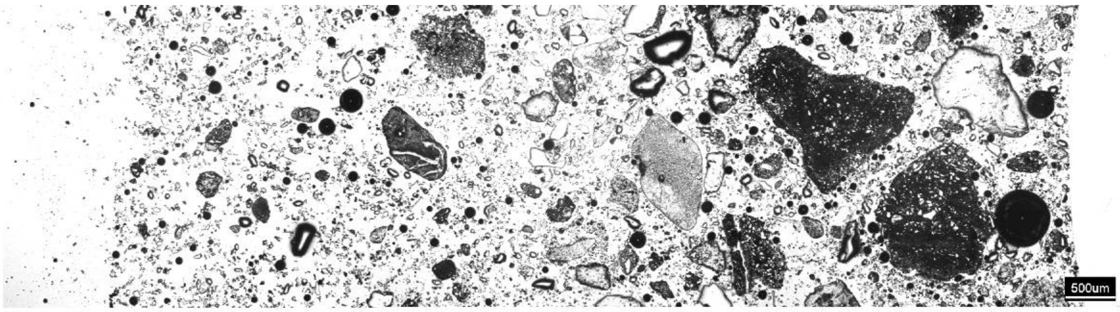

FIGURE 10 - Reflected Light Image of YPG Sand Sample

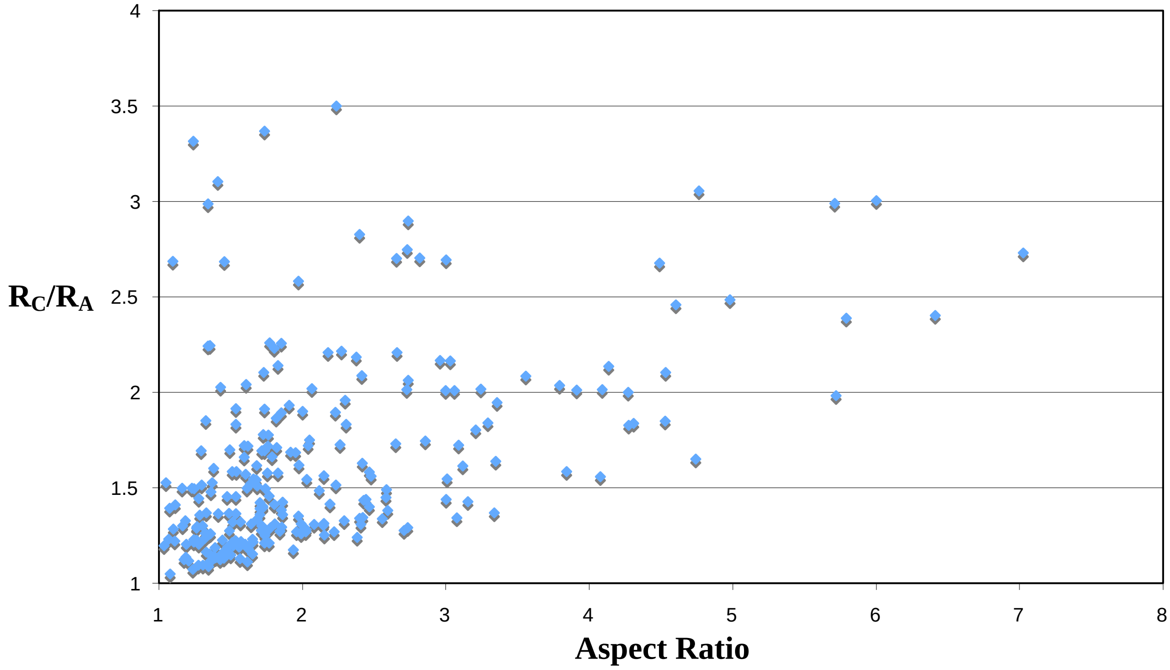

FIGURE 11 - Distribution of Iraq Sand Sample

A comparison of the distribution plot of Figure 11 with standard sand erosion test media of Figure 5 or YPG sand in Figure 9 shows different R_C/R_A and aspect ratios. The mineral grains in Figure 12 are quartz, carbonates, and sparse amounts of feldspar and black oxide minerals. The grains in Figure 12 are poorly sorted.

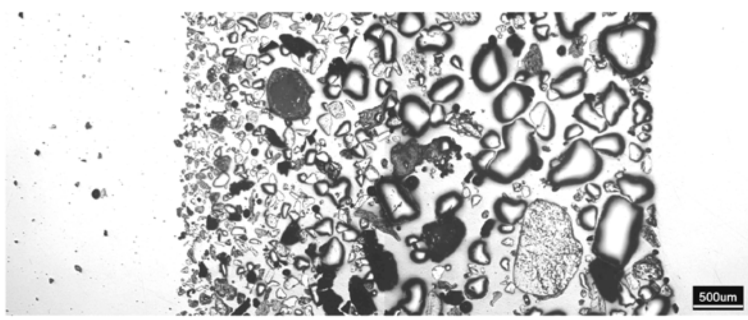

FIGURE 12 - Reflected Light Image of Iraq Sand Sample

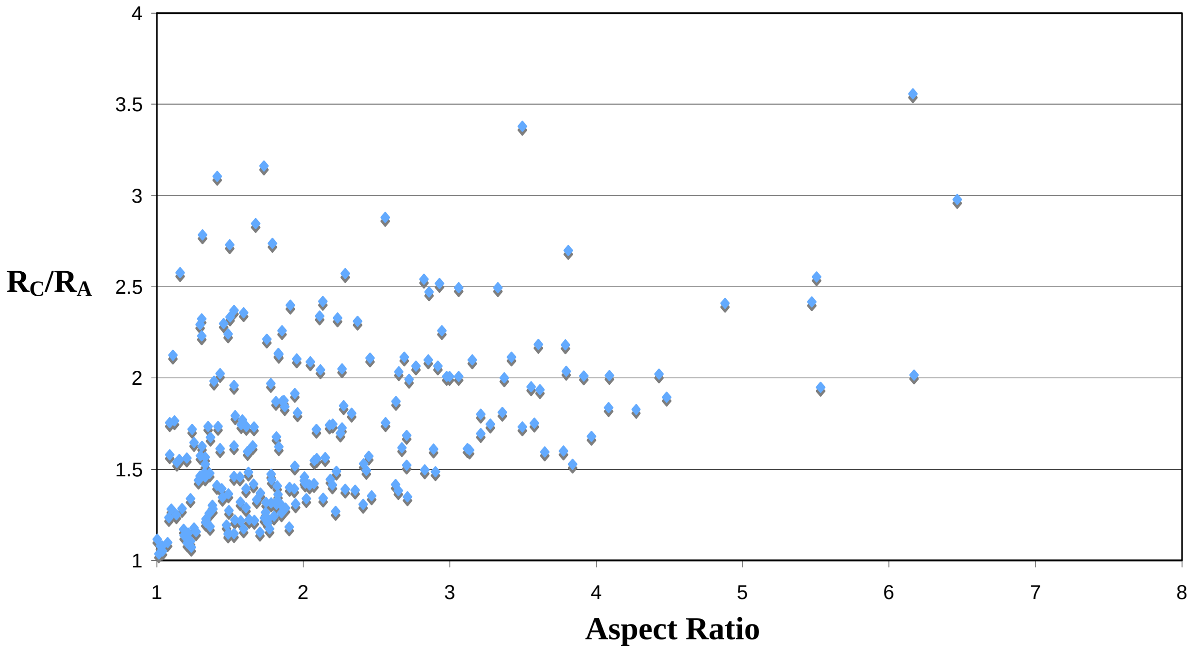

FIGURE 13 - Distribution of Afghanistan Sand Sample A

Like Figure 11, a comparison of the distribution plot of Figure 13 with standard sand erosion test media of Figure 5 or YPG sand in Figure 9 shows different R_C/R_A and aspect ratios. The mineral grains in Figure 14 are a textbook-quality example of poor sorting found in young sediments. The very large degree of grain angularity and the variation in grain sizes indicates that this material was only (geologically) recently introduced into the soil profile. The sample has the dominant polycrystalline quartz grain with other quartz grains as well as some prominent pyroxene grains. Clays and silts comprise the remainder of the material in this specimen.

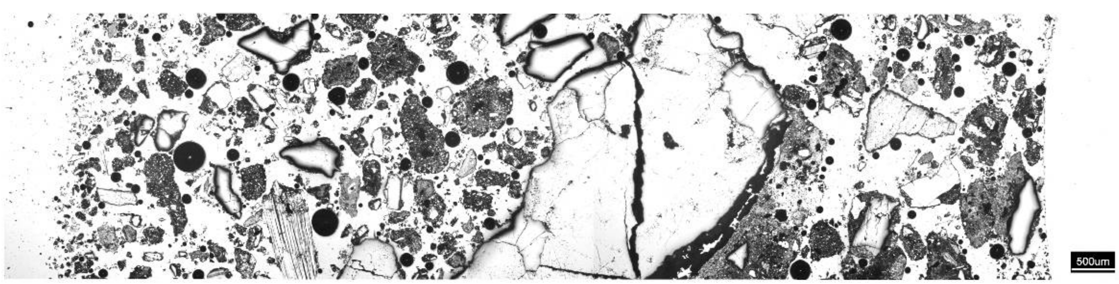

FIGURE 14 - Reflected Light Image of Afghanistan Sand Sample A

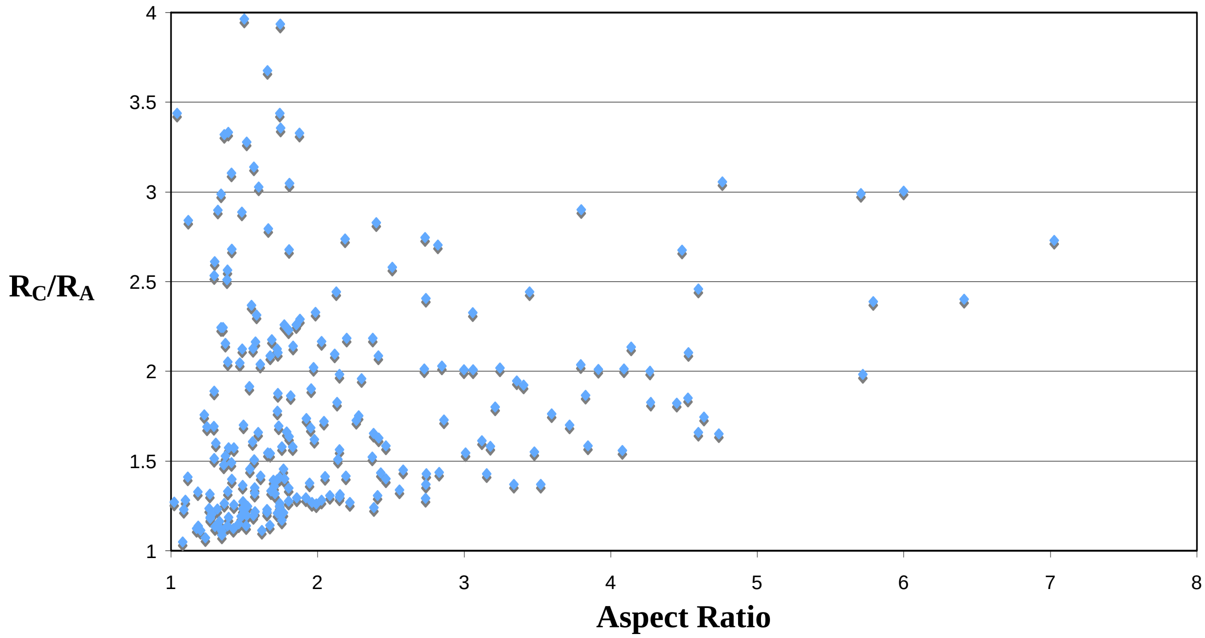

FIGURE 15 – Distribution of Afghanistan Sand Sample B

Once again, Figure 15 shows different R_C/R_A and aspect ratios when compared to Figures 5 and 9. Figure 16 is dominated by clays and silts presented in this image as the mottled grains that are obviously made of many other smaller grains. The large dark grain in the lower middle of the image has a feldspar grain at its center but has weathering products surrounding the core that are contained within the relic mineral outline. This type of morphology is termed "psuedomorphous" after the parent mineral grain. This grain would normally become fractured and the weathering products would disperse into the environment as clays and silts. Some pyroxene grains that have undergone partial alteration are also present with minor amounts of quartz grains.

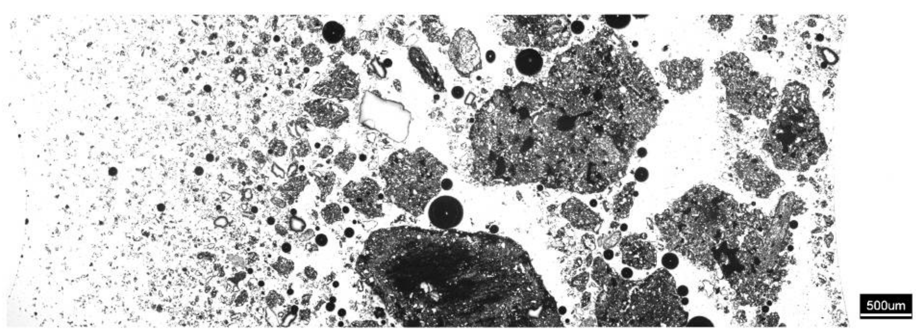

FIGURE 16 - Reflected Light Image of Afghanistan Sand Sample B

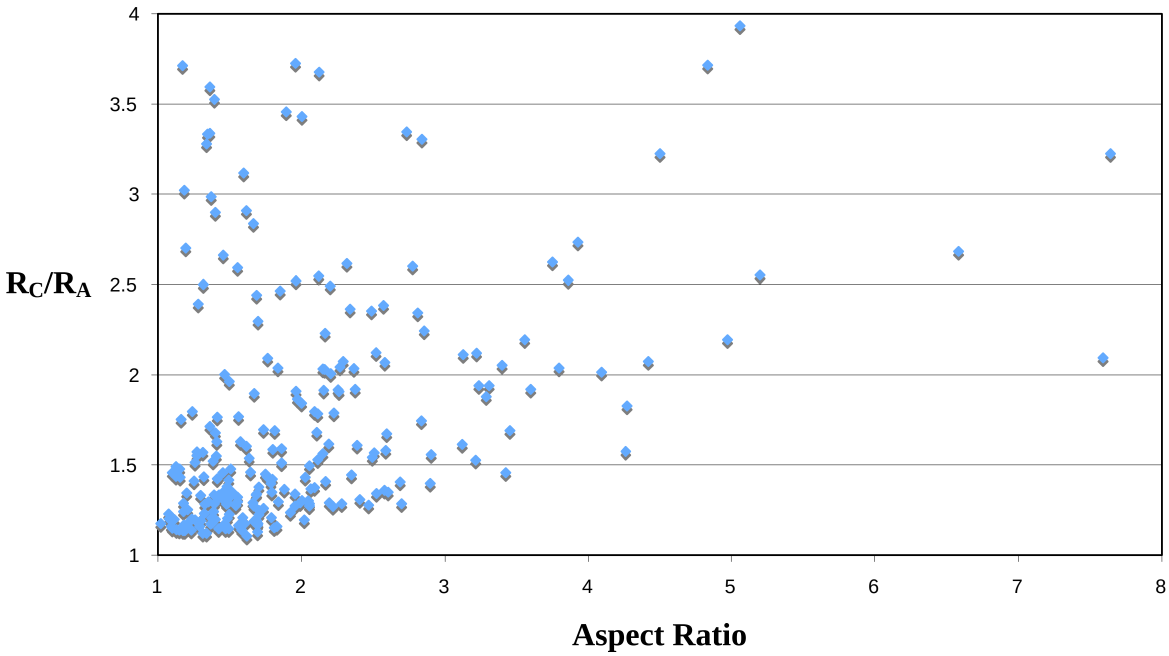

FIGURE 17 – Distribution of Kuwait Sand Sample

The last SWA sand sample in Figure 15 repeats the trend of showing different R_C/R_A and aspect ratios when compared to Figures 5 and 9. A large quartz grain dominates the image in Figure 18, however, the sample also includes numerous quartz grains, some moderate feldspar content, no visible pyroxenes or amphiboles, and some black oxide minerals. The grains in Figure 18 are very poorly sorted.

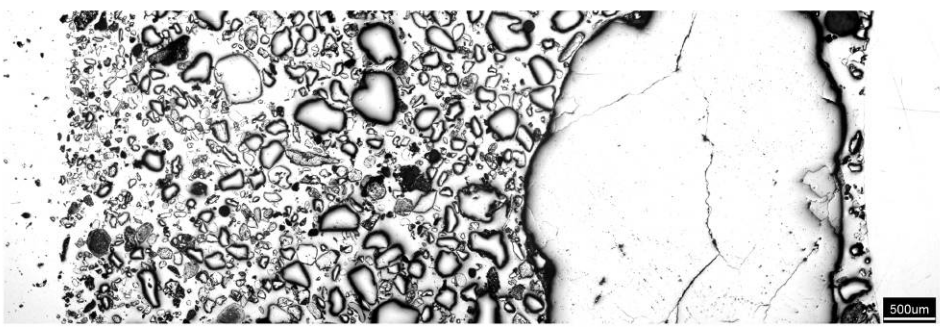

FIGURE 18 - Reflected Light Image of Kuwait Sand Sample

The plots of grain radius in Figures 19 and 20 are of the calculated radius Ra determined from the actual area of each grain. These sizes are on par with grain sizes determined by sieve and other image

analysis techniques. The single largest radius value for each sample was eliminated. The typical size profile of these samples is clear from looking at the 25 largest grains in Figure 20. The validity of this analysis is shown with the curves in Figures 19 and 20 for the two lab sieved foundry and golf sand samples for 144 R_A and 500 R_A, respectively. Both of these curves are relatively uniform across the distribution as would be expected for sieved samples. The sample designated Afghanistan B shows that the average size is very small (it is, in fact, mostly clay) but there are a number of very large grains. The sample from Kuwait is much more uniform in size with an average grain size larger than the Yuma sample, as well as the 144 to 177 micron commercially available foundry sand.

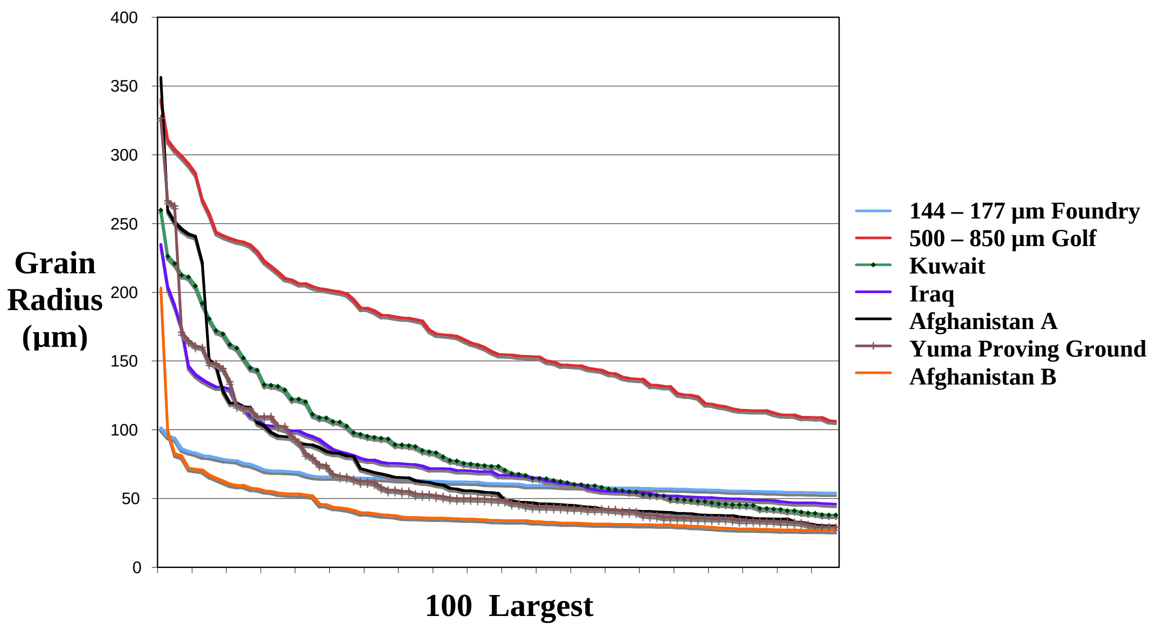

FIGURE 19 – Grain Size Distribution of 100 Largest Particles from Sand Samples

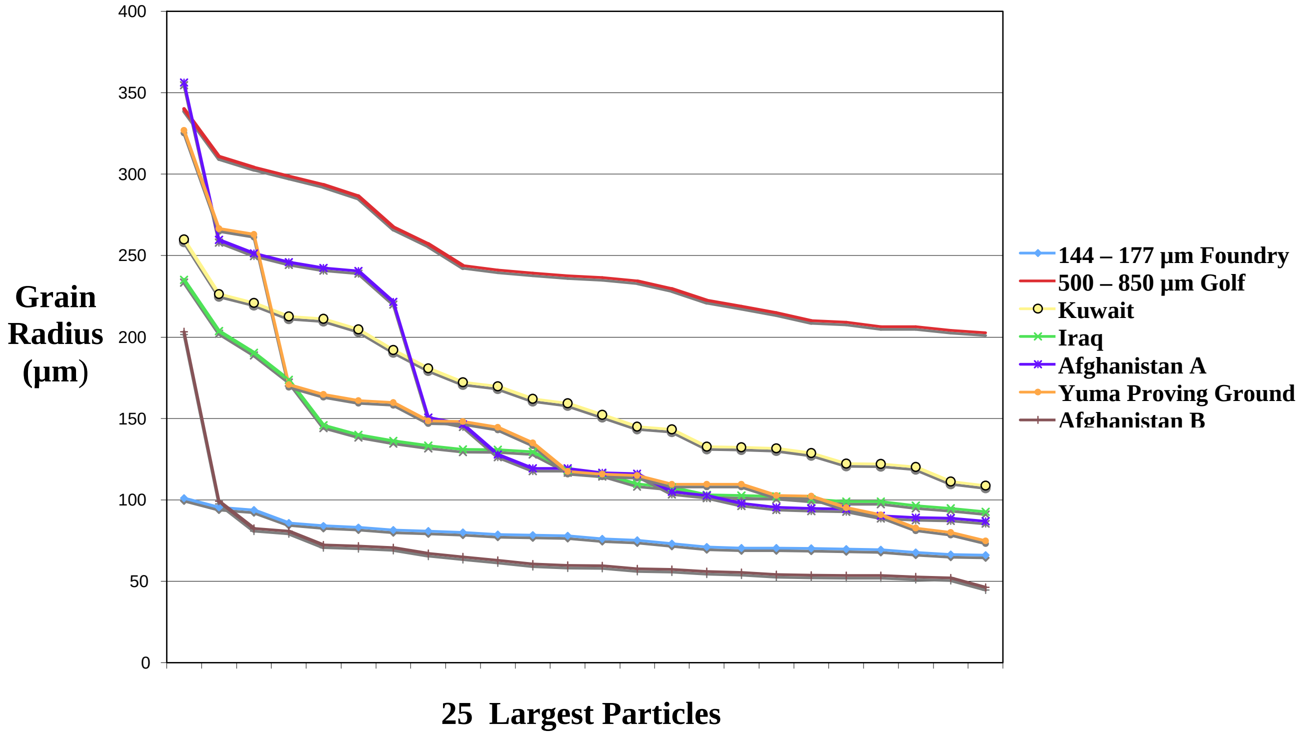

FIGURE 20 – Grain Size Distribution of 25 Largest Particles from Sand Samples

Figures 20 and 21 indicate the need to quantify both the grain size of the particles, in addition to roughness and elongation when specifying media for sand erosion testing. Although the YPG sample can be interpreted as having similar particle sizes to those found in SWA, its R_C/R_A and aspect ratios are far less than any of the SWA samples.

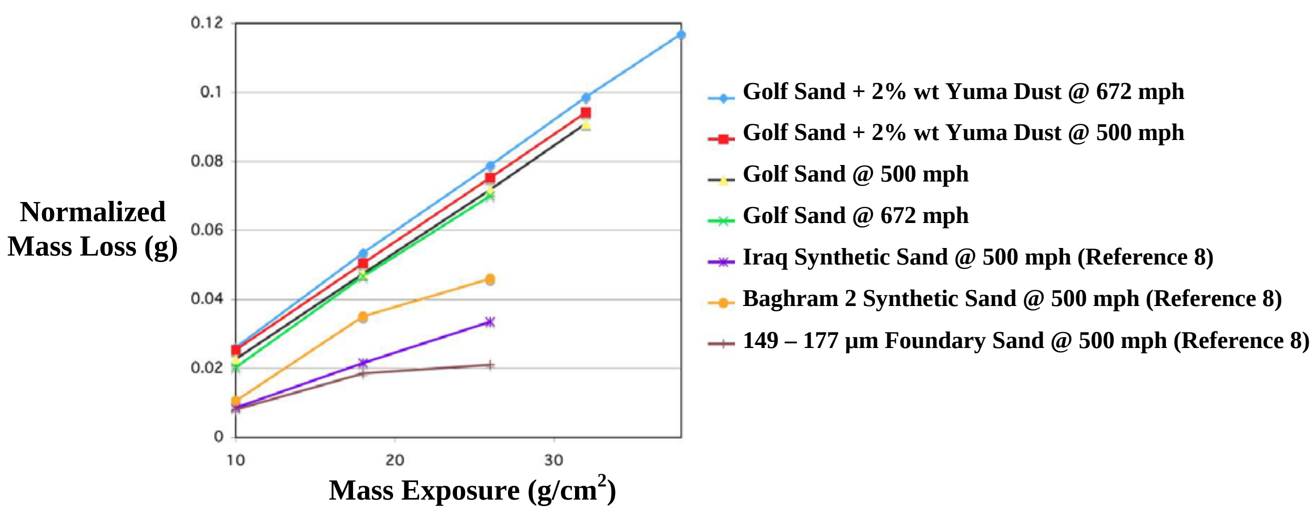

FIGURE 21 - The Relationship of Mass of Sand Exposure to Normalized Mass Loss for a Series Polyurethane Tape Samples at 30 Degree Incident Angle

Sand erosion test results are illustrated in Figure 21. Speed, media type, and presence of YPG dust were varied. Normalization was applied to the golf sand samples to compare them to data collected on smaller specimens from the ARL testing (Reference 8), in addition to foundry 149 to 177 µm sieved media. This proof of concept data shows that the effect of grain angularity coupled with size is more important than speed for equivalent mass exposures at 30 degrees incident angle for polyurethane tape. The exposure area normalized data shows that the synthetic Bagram 2 sand was more aggressive than the synthetic Iraq or the foundry 149 to 177 µm sieved media. However, the much larger and more angular golf sand sieved 500 to 850 µm was far more aggressive than any of the earlier erosion media. The data for the two different speeds of golf sand are indistinguishable at the same mass loading. Substantially slower speeds would reduce the slope of the mass-loss-to-exposure curve.

The addition of 2 weight percent of YPG dust (smaller than 100 µm) produced an enhanced material loss at both 500 and 672 mph and the loss scaled with relative speed. This data suggests that the presence of the fine YPG dust reduces the erosion resistance of the polyurethane tape and enhances the attack of sharp golf sand grains. Earlier lab results suggested that smaller diameter erosion media enhanced erosion rates in a non-intuitive manner. The above results show that much smaller powdery material added to the erosion media in a very limited amount (2 percent by weight) had a very large effect on the rate of erosion of the polyurethane tape. The tape failure is seen in the Figure 22. The width of the field of view is about 1 inch. The uniformly mottled grey area is the bulk middle of the tape. The dark spot with the lighter interior spot highlighted by the oval is the area of tape failure. The interior spot is the same color as the Yuma dust used in this test. The dark spot is the inside of the rear tape surface and the brown spot is clay caught in the adhesive backing between the tape and the aluminum substrate.

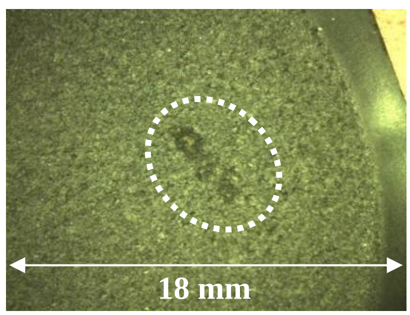

FIGURE 22 - Erosion Punch-Through in Polyurethane Tape from Exposure to 38 g/cm^2 of 500 - 850 µm Golf Sand (2X Magnification)

This preliminary data confirms that the design of an aggressive synthetic erosion media with characteristics more like the natural sand is possible by using commercially available materials.

CONCLUSIONS

Although this OSD funded effort has not been completed in its entirety, a few conclusions can be drawn from laboratory testing accomplished to date:

The test media used in military standards, including but not limited to MIL-STD-810 and MIL-HDBK-310, do not represent sand encountered in a dry-arid theatre of operations. Media from

SWA locations appear to be the more severe than test media used in conventional erosion test facilities. Sand analysis of samples from SWA countries resulted in the positive identification of highly angular silica grains, the presence of other angular minerals, and the presence of clay, all of which are not accounted for in those specifications addressing sand erosion testing. Identification of the type of clay and the mineral hardness of sands present in SWA samples and assessment of grain mount specimens must still be accomplished. In addition, the identification of a synthetic sand mixture from commercially available media more representative of these natural sand samples will be accomplished as a part of this effort.

Additional studies must be accomplished to fully screen baseline rotor blade protective systems for a variety of speeds, angles of exposures, and mass exposures before conclusions can be draw on trends for elastomeric and metallic materials. Additional materials to be tested as baselines are systems currently qualified for use on rotor blade leading edges which include three metallic systems, one polyurethane tape, one chemical agent resistant coating, one premolded elastomeric boot, and one elastomeric adhesive.

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1	DIRECTOR US ARMY RESEARCH LAB AMSRD ARL CI OK T 2800 POWDER MILL RD ADELPHI MD 20783-1197

ABERDEEN PROVING GROUND

1	DIR USARL AMSRD ARL CI OK TP (BLDG 4600)

NO. OF
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5	AFRL/MLSSO L PFLEDDERER 2179 12TH ST RM 122 WRIGHT PATTERSON AFB OH 45433-7718

ABERDEEN PROVING GROUND

5	DIR USARL AMSRD ARL WM MC M PEPI

INTENTIONALLY LEFT BLANK.